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**FOREIGN BODY IMPACT EVENT DAMAGE
FORMATION IN COMPOSITE STRUCTURES**

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INTRODUCTION

The use of composite materials in structural applications is becoming more widely accepted. The success of composites on the Delta and Titan solid rocket motor programs clearly indicates that composite materials can be used reliably in launch vehicle hardware. Even with this success, there is still concern related to the effect of foreign body impact events on the integrity of composite structures. The manufacturing, storage, transportation, and service environments are filled with foreign body impact event scenarios. Some of these scenarios can severely degrade the integrity of the composite structure; however, many will have little or no effect at all on structural integrity. A methodology for determining the severity and residual effects of foreign body impact events on composite structures has yet to be developed and accepted by the composite materials community. As a result, current flight hardware that is knowingly subjected to a significant impact event is removed from service.

This overly conservative approach to dispositioning composite structures subjected to impact events was recently used to remove a TOS-2 Kevlar motor case from service. This incident refocused NASA MSFC's attention on the need to develop a methodology for assessing the extent and effect of impact related damage on composite structures. The RTOP entitled *Filament Wound Composite Pressure Vessel Damage Tolerance Program* was conceived in March 1992 and funded in July 1992 at NASA MSFC to address this need. The scope of this RTOP includes development of Non-Destructive Evaluation (NDE) techniques, subscale testing, and analytical model development.

One aspect of the analytical model development task is the development of an analytical methodology that can be used to evaluate the experimental data, predict damage formation and modes, and predict the residual properties of an impacted composite structure. Several methodologies have successfully predicted the response of composite structures to impact events [1,2,3,4] and the scaling of impact events up to the point of damage initiation [5,6,7]. However, methodologies for predicting damage formation [8,9] to date have been either empirical or material specific.

The remainder of this report will discuss a methodology that can be used to assess the effect of foreign body impacts on composite structural integrity. The described effort focuses on modeling the effect of a central impact on a 5 3/4" filament wound test article. The discussion will commence with details of the material modeling that was used to establish the input properties for the analytical model. This discussion is followed by an overview of the impact assessment methodology. Finally, the progress on this effort to date will be reviewed along with a discussion of tasks that have yet to be completed.

MATERIAL PROPERTIES

The success of modeling the 5 3/4" bottle shown in Figure 1 is dependent on the accuracy of the material properties input to the models. The bottle configuration contains four different types of materials: rubber liner, inert propellant, steel boss, and composite outer layer. The material properties for the liner, propellant, and boss are summarized in Table 1. These materials are all isotropic and, for the loading being considered, behave in a linear-elastic

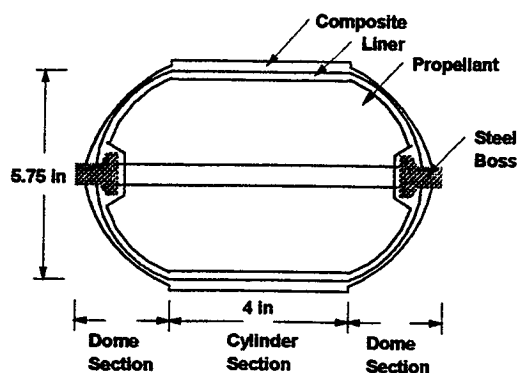


Figure 1: Illustration of 5 3/4" bottle

Table 1: Isotropic material properties for 5.75" bottle

| | E (psi) | ν |
|------------------|----------------------|-------|
| Steel Boss | 30(10 ⁶) | 0.3 |
| Liner | 1,440 | 0.49 |
| Inert Propellant | 800 | 0.49 |

manner. The composite outer layer is the primary load bearing component of the bottle. The composite constituent materials used are IM7 fibers embedded in 8553-45 matrix material.

To fully model the response of the bottle to a central impact event and evaluate its residual properties, material properties of the composite layer at the constituent, lamina, and laminate level are required. Effective constituent properties were determined using vendor supplied unidirectional property data and micro-mechanics models. Micro-mechanics, variational principals, and lamination theory were employed to compute the properties of the composite laminate in the cylinder and dome sections of the bottle. In the cylinder section of the bottle the laminate is filament wound into a $[90_2/\pm 11.5/90_2/\pm 11.5]$ configuration. The resulting orthotropic material properties are:

$$E_a = 12.7 \text{ Msi}$$

$$E_\theta = 13.6 \text{ Msi}$$

$$E_r = 1.34 \text{ Msi}$$

$$\nu_{a\theta} = 0.002$$

$$\nu_{\theta r} = 0.345$$

$$\nu_{ar} = 0.345$$

$$G_{a\theta} = 9.55 \text{ Msi}$$

$$G_{\theta r} = 5.32 \text{ Msi}$$

$$G_{ar} = 4.95 \text{ Msi}$$

where the coordinate directions are defined as a-axial (along the length of the bottle), θ -circumferential direction, and r-radial direction.

The complex laminate configuration in the dome section of the bottle is a result of the polar wind used to fabricate the bottles. As a result the laminate configuration and thickness change continuously from the top of the dome (at the cylinder/dome intersection) to the bottom of the dome (at the boss). Thus the material properties in this region are continually changing as shown in Figure 2 and become extremely anisotropic. For modeling purposes the three dimensional anisotropic material properties for the dome were computed at discrete increments along the curvature of the dome. The laminate configuration at discrete increments were computed using a contractor

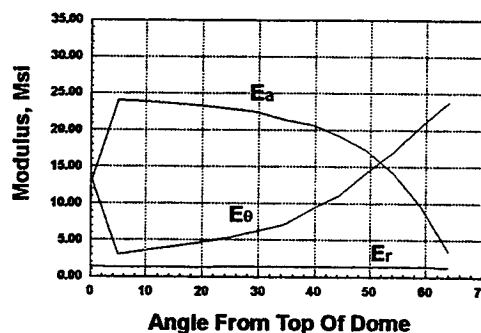


Figure 2: Variation of dome properties

supplied model. The discrete increments were chosen to correspond to the location of element center points in the finite element model used to predict the impact response.

MODEL DEVELOPMENT

The modeling of the 5 3/4" bottle shown in Figure 1 requires a systematic simplification of the complex phenomenon associated with the impact event. Because of the relatively high ratio of the impactor mass to effective bottle mass, the effect of the higher order vibration modes can be ignored enabling the use of a static analysis [3]. The static analysis employed involves various levels of modeling starting at the global or full structural level and ending at the micro-mechanics level. This step wise approach is taken in order to facilitate the determination of fiber and matrix phase averaged stresses in the composite layer that result from the impact event while at the same time making efficient use of computer resources. The phase averaged stresses in the composite are used to predict damage and eventually residual properties of the bottle.

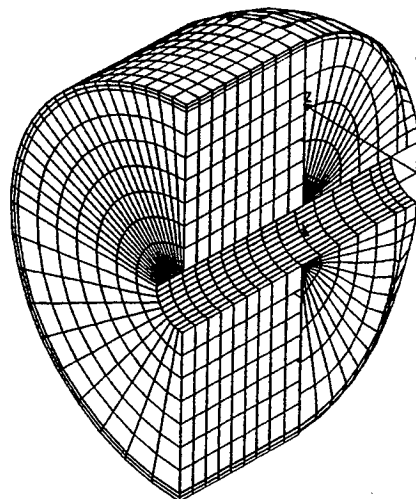


Figure 3: Global finite element mesh of bottle

The global or full structural model employs the use of the finite element technique. The finite element mesh used in this investigation is shown in Figure 3. At this level the composite is modeled as a single layer of homogeneous material. The finite element model takes advantage of the symmetry associated with the bottle geometry. On the symmetric surfaces the displacements normal to the surface and rotations parallel to the surfaces are constrained from movement. In addition, a constraint representing the cradle used to hold the bottle is also imposed. This constraint restricts radial displacements in the cylinder section of the bottle along a 1/2" wide strip that adjoins the dome and circumferentially starts at the bottom of the bottle and ends half way up the bottle's side. The purpose of this model is to define displacements along a boundary region that is local to the impact event. Because this region will be chosen away from the actual impact event a point load is used to represent the force of the impactor tup on the bottle at the top intersection of the symmetric surfaces. As a result of this loading condition a maximum displacement of 0.1" is produced at the point of impact. Figure

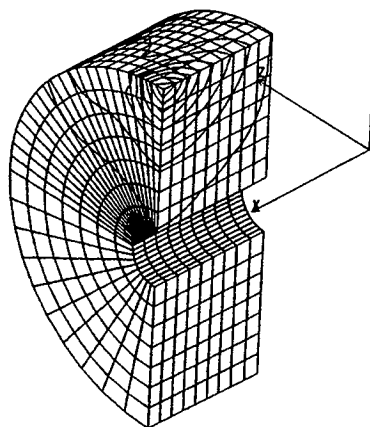


Figure 4: Displacement contours in bottle resulting from the impact event.

4 illustrates the displacement contours for the impact event that was produced using the above described model.

The second step in the modeling process models the region local to the impact event using a finer finite element mesh. At this level each layer of the composite is modeled as a unidirectional ply. The displacements calculated using the global finite element analysis are used as the boundary conditions for the local finite element mesh. Since the local mesh will have more nodal points along all of the boundaries, polynomials are fit through the results of the global analysis in order assist in the estimation of the proper nodal constraints on the boundary surfaces of the local finite element mesh. The load resulting from the impact event in this model is modeled as a elliptical pressure distribution [10]. The resulting stress distributions in the individual plies are then calculated. These results are then used by a micro-mechanical analysis that computes the phase (constituent) averaged stresses. Knowing the phase averaged stresses, damage in the constituent phases are predicted. These predictions are then used to degrade the material properties in the damage regions in order to calculate the residual properties of the bottle.

PROGRESS, TASKS REMAINING, RECOMMENDATIONS

The above described effort has made significant progress this summer. The modeling of all the materials in the bottle has been completed. Some of the material properties were experimentally verified. The global finite element analysis has also been completed and the displacements in the region of the impact event have been determined. Currently, the construction of the local finite element model is in progress. The micro-mechanical models that will be used to predict the constituent phased averaged stress using the results of the local finite element model have already been constructed. The 5 3/4" bottles were impacted earlier this year at NASA MSFC. Correlations between the model predictions and the observed damage remain to be made.

As a result of this summers efforts the following recommendations are made to help improve NASA MSFC's capability to predicting the response of composite structures to foreign impact events:

- 1) The current model for the geometry of the composite in the dome requires modification to account for tow width and the use of helical winds.
- 2) A user subroutine needs to be developed that will allow the local finite element code to have direct access to the micro-mechanical models. This will enable progressive damage analysis of impact events to be performed.
- 3) An effort should be initiated to develop a model that will predict the residual properties of the composite bottles after they have been impacted.
- 4) The 18" bottles that are slated for testing in FY '95 should be modeled using the above methodology to verify the approach taken.

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